

Report Documentation Page			Form Approved OMB No. 0704-0188	
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1 AGENCY USE ONLY (Leave Blank)	2. REPORT DATE 20 October 1999	3. REPORT TYPE AND DATES COVERED Draft report, dates covered May to October 1999		
4. TITLE AND SUBTITLE SBIR phase I report topic BMDO 99-013 High Thermal Conductivity Composite Structures		5. FUNDING NUMBERS Contract number N00167-99-C-0047		
6. AUTHOR(S) John Bootle				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) XC Associates, Inc 28 South Main Street Berlin, NY 12022		8. PERFORMING ORGANIZATION REPORT NUMBER 9904-01		
9. SPONSORING/ MONITORING AGENCY NAME(S) AND ADDRESS(ES) Al Bertram Naval Surface Warfare Center Carderock Division Code 681 9500 MacArthur Boulevard West Bethesda, MD 20817-5700		10. SPONSORING/ MONITORING AGENCY REPORT NUMBER		
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION /AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE; SBIR REPORT, DISTRIBUTION UNLIMITED		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words)				
14. SUBJECT TERMS HIGH THERMAL CONDUCTIVITY COMPOSITE, ENHANCED Kz, THERMAL MANAGEMENT LIGHTWEIGHT THERMAL PLANES, SPACECRAFT THERMAL RADIATORS			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

NSN 7540-01-280-5500

Standard form 298 (rev 2-89)

DTIC QUALITY INSPECTED 4

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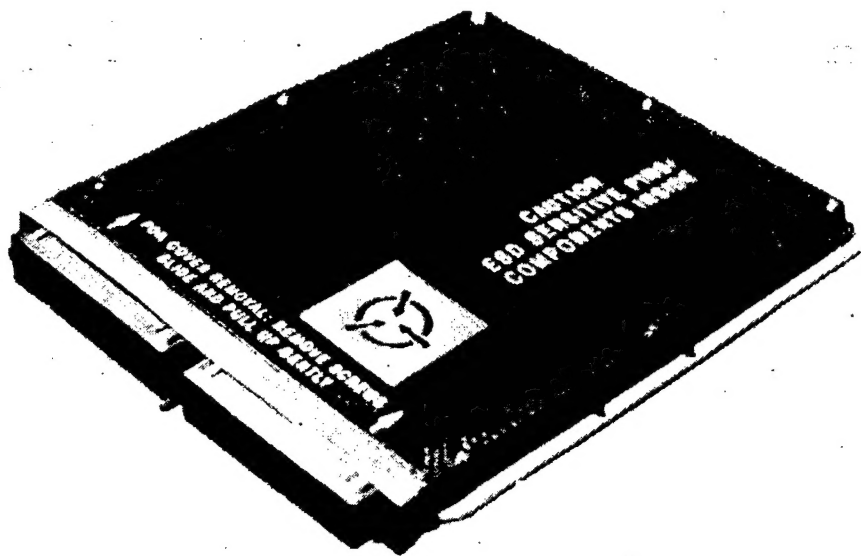
## 1 Introduction

The work accomplished in this SBIR project demonstrated that the addition of boron nitride (BN) powder to a composite laminate significantly increases the through the thickness thermal conductivity ( $K_z$ ) of a composite laminate. The importance of this work is that the improved  $K_z$  results in significantly lower operating temperatures for thermal applications such as composite thermal planes and space based radiators.

Typical composite thermal planes have an in-plane thermal conductivity ( $K_x$  &  $K_y$ ) in the range 300-650 w/m/K. based on the fiber selection. But, the relatively low  $K_z$  of a typical composite laminate significantly reduces the efficiency of the thermal plane due to the high impedance to getting heat in or out of the laminate. Finite element analysis of typical composite thermal planes shows that by increasing the  $K_z$  from about 1 w/m/K for a typical laminate to about 4 w/m/K, as achieved in this project, results in temperature reductions in the order of 30%.

This project was carried out using AMOCO K800x fiber, but since the resin, rather than the fiber dominate  $K_z$ , the improvement in  $K_z$  is expected to be applicable to any carbon fiber laminate.

A number of companies have expressed and interest in the work carried out during this project and XCA are working with them to determine the best route to proceed with the work to a Phase II.

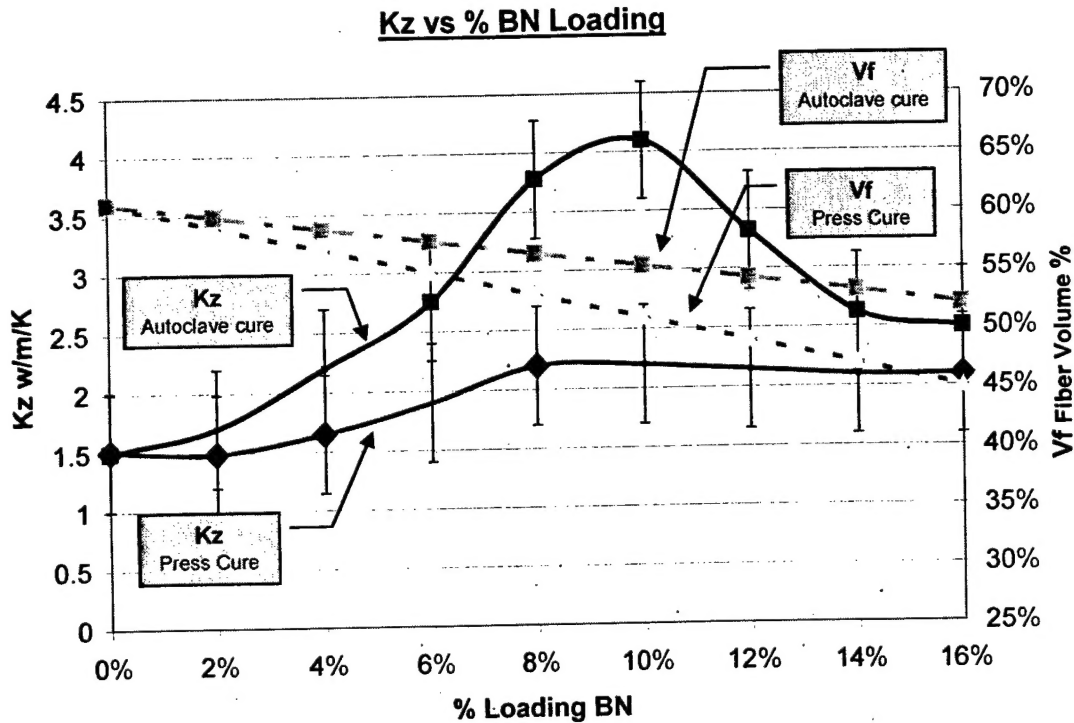


**Figure 1, photograph of typical composite thermal core and covers fabricated by XC Associates**

## 2 Thermal results

The addition of boron nitride powder, BN, to a composite laminate increased the through thickness thermal conductivity,  $K_z$ , but decreased the in-plane thermal conductivity,  $K_x$  &  $K_y$ . The gain in  $K_z$  was greater than the loss in  $K_x$  so the net result was an improvement in overall thermal performance as discussed in paragraph 2.4.

### 2.1 Thermal conductivity $K_z$



**Figure 1**

The graph in Figure 1 shows that as BN is added the thermal conductivity  $K_z$ , of the laminate increases.

#### 2.1.1 Description of graph

Laminate samples were cured using press cure during which there was very little resin bled from the laminate. During the autoclave cure cycle resin was bled from the laminate. The fiber fraction was calculated from the cured thickness of the laminate after cure.

The thermal conductivity,  $K_z$ , of the samples was measured using the laser flash method, which measured the diffusivity, specific heat and density of the samples.

$$K = \alpha \cdot \rho \cdot C_p \quad \text{equation 1}$$

Where

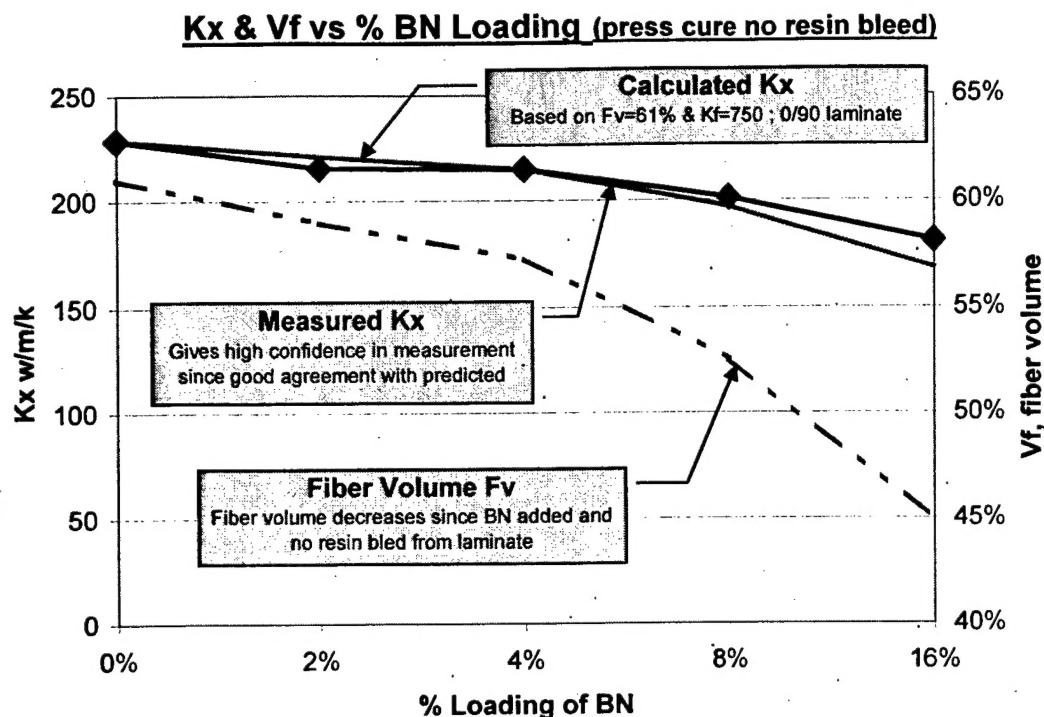
$\alpha$  = Thermal diffusivity

$\rho$  = Density of laminate, 1.8 gr/cm<sup>3</sup> @25°C

$C_p$  = specific heat of laminate, 0.85 J/gr. Deg @ 25°C

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## 2.2 Thermal conductivity Kz



**Figure 2**

### 2.2.1 Description of graph

The graph in Figure 2 shows the variation of the measured Kx against the calculated fiber volume for the press-cured samples. (The laminate was a 0°/90° laminate so Kx=Ky).

The fiber thermal conductivity of about 750 w/m/K was derived from data from AMOCO for the K800X fiber.

## 2.3 Discussion of results

2.3.1 The laminates were fabricated by adding a predetermined weight of BN powder to each layer of a prepreg during the lay-up process. Since material was being added to the prepreg the volume increased and hence the fiber volume, Vf, decreased as more BN was added. This is important since in-plane thermal conductivity Kx & Ky determined by the relationship

$$K_L = K_f V_f + K_m V_m \approx K_f V_f$$

**Equation 2**

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The thermal conductivity of the laminate is dominated by the fiber since  $K_f \gg K_m$ . If the fibers are not orientated along the heat flow direction the equation is modified as

$$K_x = K_L \sin^2 \phi \qquad K_y = K_L \cos^2 \phi \qquad \text{Equation 3}$$

Where

$\phi$  = angle of fibers of particular ply  
 $K_f$  = Longitudinal thermal conductivity of fiber  
 $K_m$  = Thermal conductivity of matrix  
 $V_f$  = Fiber volume  
 $V_m$  = matrix fiber volume

From equations 2 & 3 it can be seen that the thermal conductivity,  $K_x$  &  $K_y$  are controlled by the fiber conductivity since this is much greater than the resin conductivity.

- 2.3.2 Figure 2, shows the measured in-plane thermal conductivity for the press cured samples, the theoretical  $K_x$  calculated from equations 2 & 3 is also plotted on the same graph with the corresponding fiber volume,  $V_f$ . The close agreement of the theoretical and measured results gives high confidence in the laser flash method to derive the thermal conductivity.
- 2.3.3 There was considerable scatter in the results of  $K_z$  obtained from different autoclave cured samples. The reason appears to be that the resin bleed varied between samples, indicating this is an important variable. More work needs to be carried out in this area.
- 2.3.4 Since the resin dominates the  $K_z$  it is expected that the improvement in  $K_z$  presented above will also be applicable to laminates fabricated from other fibers.
- 2.3.5 A preliminary investigation based on 2 samples showed that larger particle sizes resulted in less improvement in  $K_z$ . The effect of smaller particle sizes needs to be investigated.

## 2.4 Practical importance of the results

Using the measured  $K_z$  results from Figure 1, and calculating the corresponding  $K_x$  &  $K_y$  (from equations 2&3) the temperature of a typical SEM-E thermal plane was calculated and showed that the addition of 8%-10% BN to a laminate results in a 30% temperature reduction. This analysis assumed a typical SEM-E heatsink loaded with 65 watts of heat applied uniformly across the center of the heatsink while the rails were maintained at temperature  $T_0$ . A graph of the temperature difference  $\Delta T$  is presented in Figure 3.

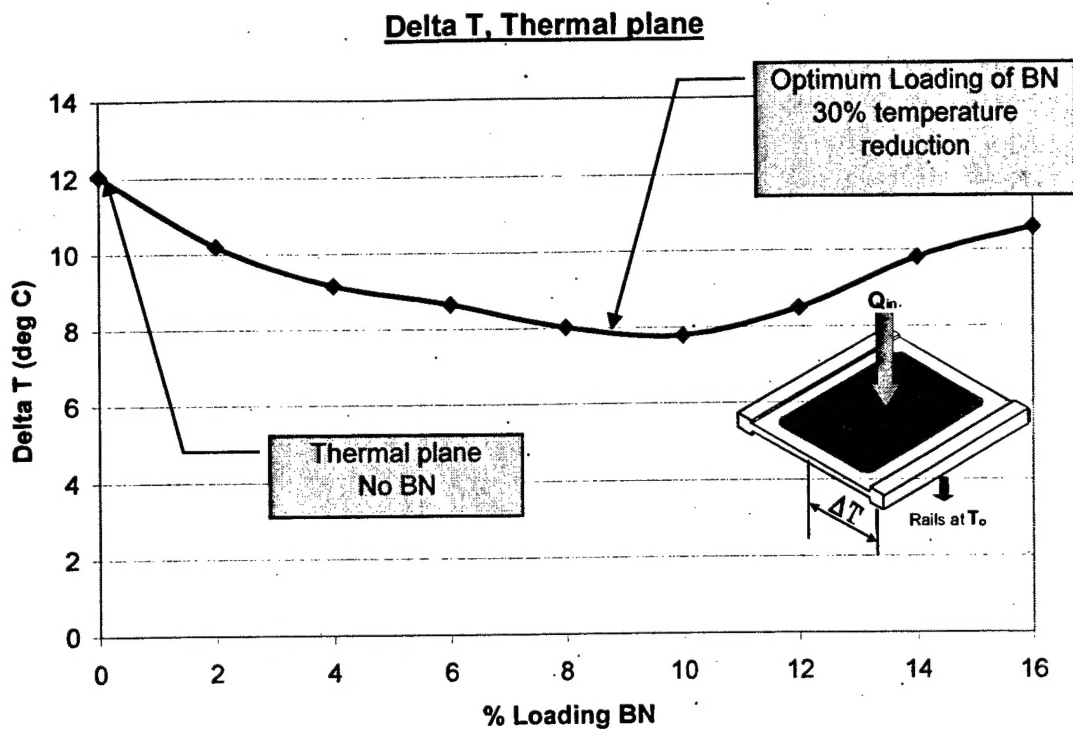
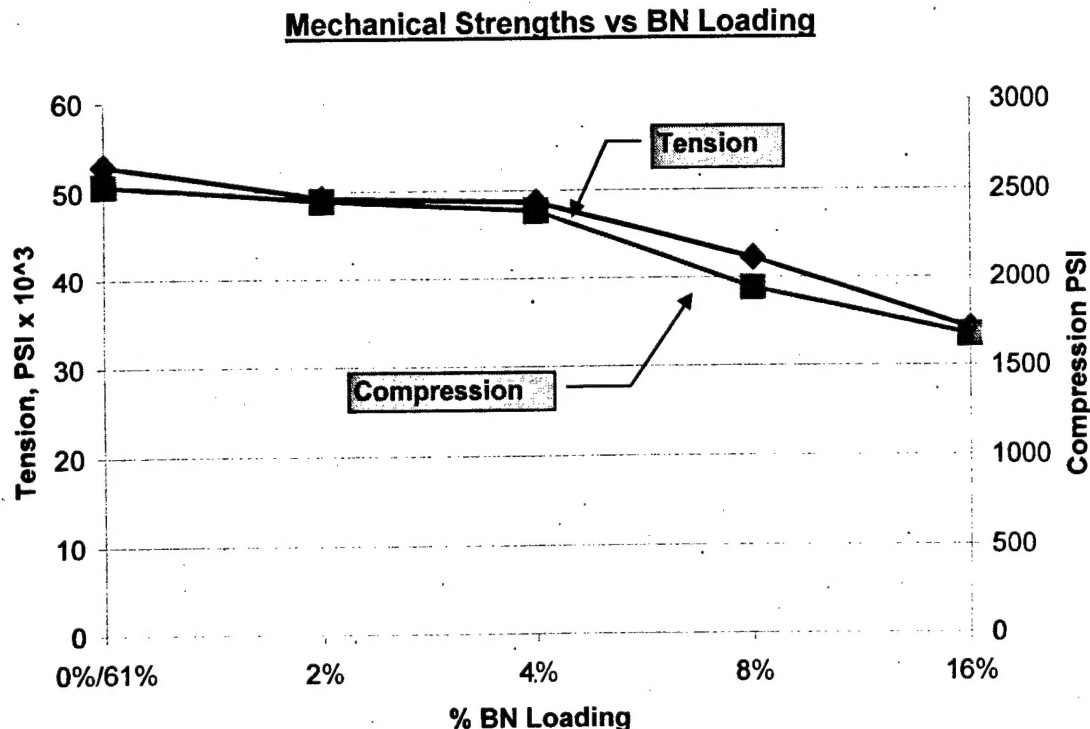


Figure 3



## 3 Mechanical results

The mechanical results indicate that the addition of BN powder reduces the laminate strength therefore the optimum loading of BN must be chosen to meet the both the thermal and mechanical requirements for the particular application. Using the method of fabrication described in paragraph 5, Fabrication method, it is straightforward to only add BN to the areas with high thermal input and hence achieve the highest structural strength.



The mechanical testing ongoing, the full results will be published in the final report.

### 3.1 Mechanical test samples

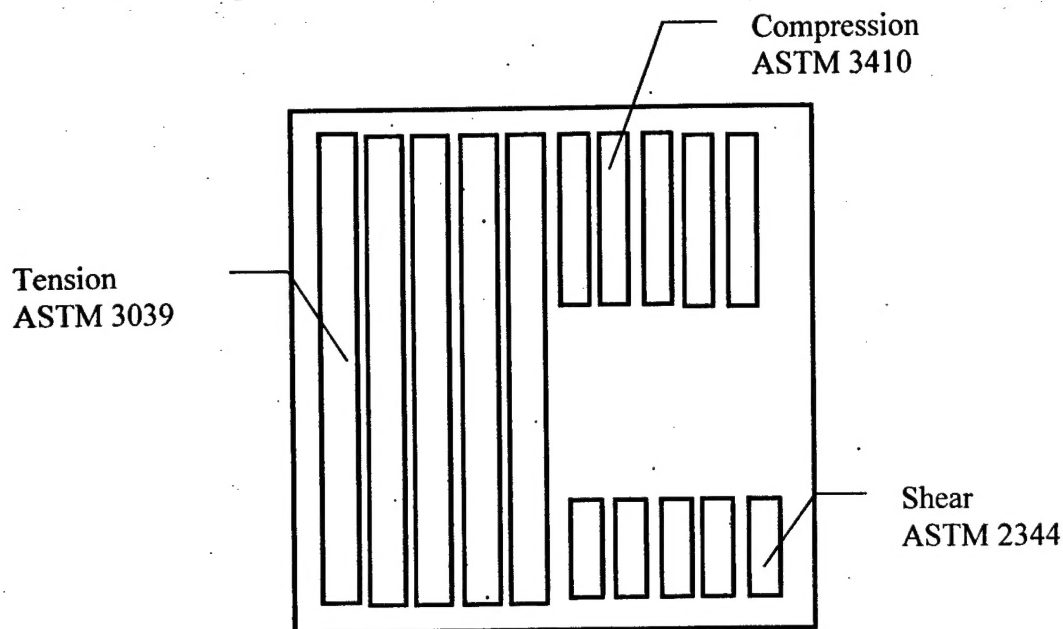
3.1.1 The following tests were used to characterize the laminate, mechanical tests were only carried out the press cured samples.

Test	ASTM	Comment
Tension	ASTM D 3039	5 test coupons from each sample
Short beam shear	ASTM D 2344	5 test coupons from each sample
Compression	ASTM D 3410	5 test coupons from each sample

Table 1

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The test samples were cut from a 12" x 12" x 0.1" thick laminate as shown in Figure 4



**Figure 4**

3.1.2 Proff Ron Bucinell of Union College is carrying out the mechanical testing.

## 3.2 Microscopic

Samples were polished and examined under a microscope to determine the location of the fibers, location of the BN and void content. Steve Perrucci of Union College is carrying out this work as part of his senior project. The full results will be presented in the final report.

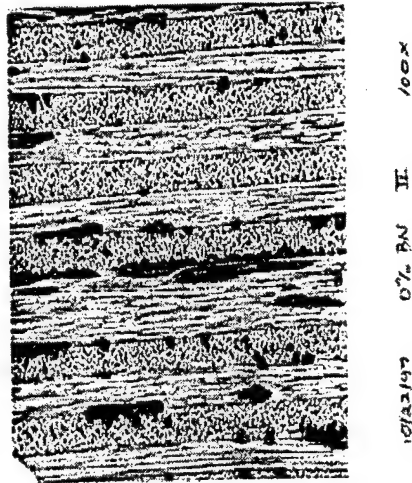


Figure 5, 0% BN

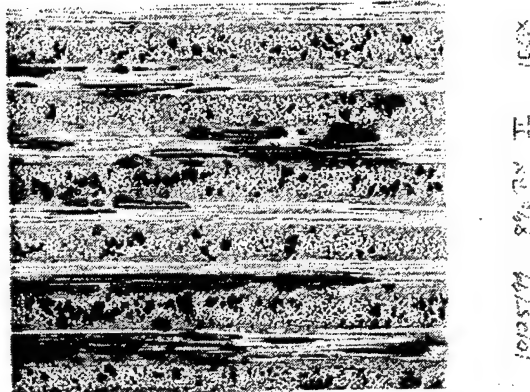
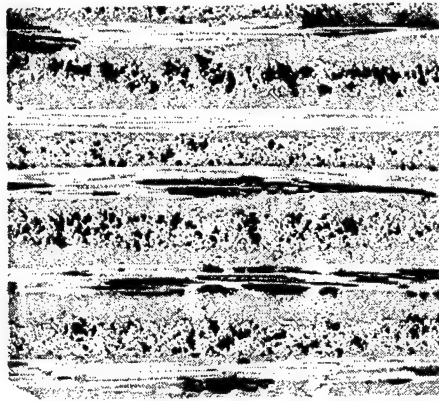


Figure 6, 8% BN



**Figure 7, 16% BN**

## 4 Materials

Material	Supplier	Specification
Fiber	AMOCO	K800x
Prepreg	Hexcel	K800x 2K/954 R/C: 33% ( by weight) FAW: $83 \pm 5 \text{ G/M}^2$ Fiber Volume 61%
Boron Nitride	Advanced Ceramics	Polar Therm 620

**Table 2**

### 4.1 Material selection

4.1.1 The choice of K800x fiber was based on availability and cost rather than any other technical reasons.

4.1.2 Since Kz is mainly dependent on the matrix it is believed that the results presented will also apply to laminated fabricated from other fibers.

4.1.3 Boron Nitride was selected as the loading material to enhance Kz

- It is inert and will not cause corrosion
- Compatibility of coefficient of thermal expansion
- Commercial availability
- A Literature survey indicated BN powder significantly improved the thermal conductivity of compression molding compounds.
- Density and structure of BN is similar to carbon.

## 5 Fabrication method

The laminates were fabricated by simply adding a predetermined weight of BN powder to plies of prepreg during a normal lay-up process. The laminates were then cured using the Hexcel recommended cure cycle for either press or autoclave.

### 5.1 Selection of fabrication method

The most important reasons for selecting this method of fabrication in preference to mixing the BN with the resin prior to prepregging is because

- 5.1.1 It is possible to load only specific areas of laminate subject to high thermal inputs. This is particularly important for high performance structural applications see XXX
- 5.1.2 It is very simple to carry out, particularly in small batch fabrication and lower cost than having the "prepregger" blend the powder during prepreg operation.

### 5.2 Details of fabrication method

Specific quantities of BN added are presented in Table 3

% of BN added to laminate	Weight grams/in <sup>2</sup>
0%	0.00000
2%	0.00258
4%	0.00516
6%	0.00774
8%	0.01032
10%	0.01290
12%	0.01548
14%	0.01806
16%	0.02064

**Table 3**

The area of each ply was calculated and the weight of BN to be added was simply calculated by multiplying the area by the weight given in Table 3. A more detailed description is presented in US patent 5,962,348.

## **6 Future Work**

### **6.1 Computer Model**

Develop computer model of laminates to predict the thermal and mechanical behavior. This appears to be a very useful tool to use as a method to analysis candidate laminates to determine the critical factors influencing thermal conductivity. Prior work by XCA and others has demonstrated the Kz is influenced by a large number of variables and that it would impractical to build physical laminates and test each candidate and that a use of a computer code greatly assist with optimization.

### **6.2 Validate computer predictions**

The computer code will be validated by the construction and testing of samples

### **6.3 Plating**

XCA have identified plating as a significant issue for composite components. In prior work XCA have successfully plated composite thermal cores using Ni/Cad/Chromate with excellent adhesion that has resisted 500hr. salt spray testing. But this testing required considerable surface preparation that resulted in a 64 surface finish. XCA believe that it is possible to modify the surface treatment using a corona discharge that will result in a surface better than 32.

### **6.4 Identify programs**

XCA has identified a number of programs that are interested in enhanced thermal conductivity composite laminates. We are working with the companies shown in Table 4, to identify programs that have a particular requirement .

### **6.5 Production method**

Once programs have been identified it will be important to develop an automated method of production that will spread the require weight of BN powder in the correct areas of the laminate.

## 7 Commercialization

*Not for public distribution*

**Table 4**